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MONTHLY WEATHER REVIEW

JAMES E. CASKEY, JR., Editor

Volume 88
Number 2

FEBRUARY 1960

Closed April 15, 1960
Issued May 15, 1960

A PRELIMINARY REPORT ON OZONE OBSERVATIONS AT LITTLE AMERICA, ANTARCTICA[1]

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[Manuscript received December 11, 1959; revised January 28, 1960]

ABSTRACT

Summaries of ozone measurements made at Little America, Antarctica during 1957 and 1958 are presented. Data include both total ozone observations made with a Dobson Ozone Spectrophotometer and surface ozone concentrations measured with the automatic ozone recorder developed by Regener. Wind and ozone roses were constructed to examine the variation of surface ozone with wind direction, and in addition the net meridional transport of surface ozone was computed for each month for a year.

The computed northward transport of surface ozone during the winter months of June through September suggests a model for atmospheric circulation in the Antarctic. Assuming no ozone is created or destroyed by photochemical or other means during this dark period and that Little America is representative of its latitude, steady-state conditions require that the low-level outflow of ozone be compensated by inflow at other levels. Both the lower stratospheric circumpolar jet inhibiting meridional transport and the stability of the Antarctic stratosphere inhibiting downward vertical transport lead us to ascribe the principal ozone influx to the troposphere above the surface layer. Computations of the tropospheric ozone concentrations required to replace the low-level loss of ozone, using Rubin's values for the vertical distribution of the tropospheric mass transports, are in good agreement with the observations made by ozonesonde at Halley Bay.

It thus appears that some of the ozone manufactured in the sunlit stratosphere of lower latitudes which enters the troposphere through the tropopause gap associated with the mid-latitude jet stream is transported into the Antarctic by winds of the vigorous winter storms which move around and into the continent, and finally sinks and then flows northward again as part of the 2- to 3-km. thick surface layer.

1. INTRODUCTION

Beginning in early 1957 measurements of surface ozone concentration and total ozone were carried out at the US-IGY Little America Station, located on the shelf ice 2½ miles south of the Ross Sea, Antarctica (78°11′S., 162°10′W., 44 meters m.s.l.). See figure 1. Air which reaches the Little America Station from east through south to west has traveled for thousands of miles over a snow field, lying on ice hundreds of feet thick. Winds from west-northwest clockwise to east-northeast have moved over predominantly sea-ice, generally not more than 10 feet thick, except during January to April when mostly open ocean or very thin ice is found. In September-October the sea-ice has its greatest extension, reaching about 1,000 miles northward. The only plant life, lichens, is found on the nearest exposed rock of the Rockefeller Mountains, 70 miles east of Little America.

To take advantage of this unique high-latitude site, a program of measurement of total ozone content in the vertical column by means of the Dobson Ozone Spectrophotometer was begun in February 1957 by W. B. Moreland and continued in 1958 by W. S. Weyant. The surface ozone program was started in late March 1957 by B. W. Harlin, also of the U.S. Weather Bureau, who installed the automatic ozone recorder developed by

[1] Presented in condensed form at the International Conference on Atmospheric Ozone—Oxford Symposium, July 1959 and at the Antarctic Symposium of Buenos Aires, November 1959.

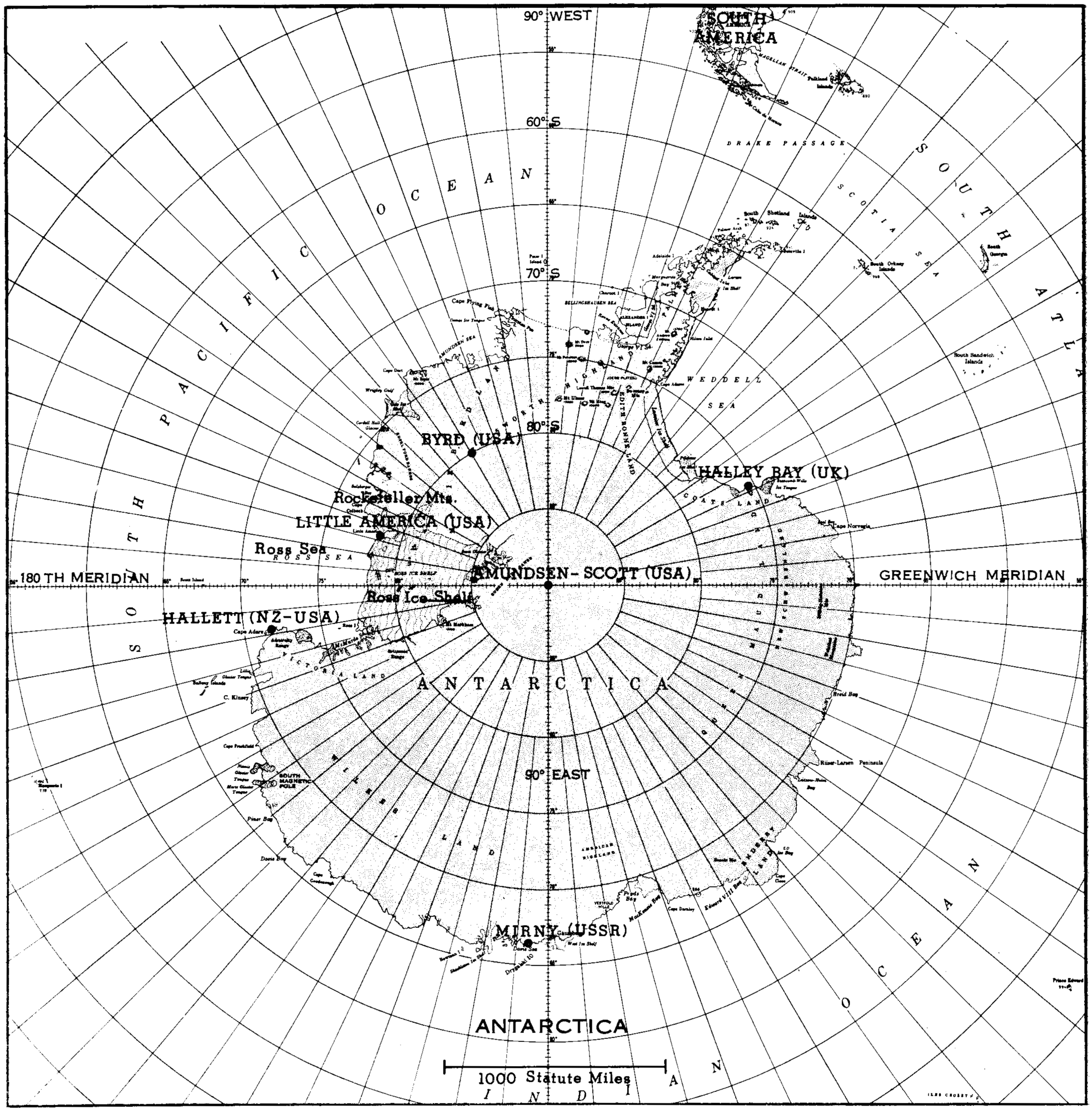

FIGURE 1.—Map of Antarctica showing sites mentioned in text.

Regener [9]; measurements were made from December 1957 through October 1958 by W. S. Weyant.

2. EXPOSURE OF INSTRUMENTS AND METHODS OF OBSERVATION

Total ozone—Measurements of total ozone were made with Dobson Ozone Spectrophotometer Number 37 located in the "Aurora Tower" (fig. 2). The instrument was so mounted that the sun-director was located under a dome which could be rotated 360 degrees. A section of the dome could be opened to permit either direct sun or zenith sky observations.

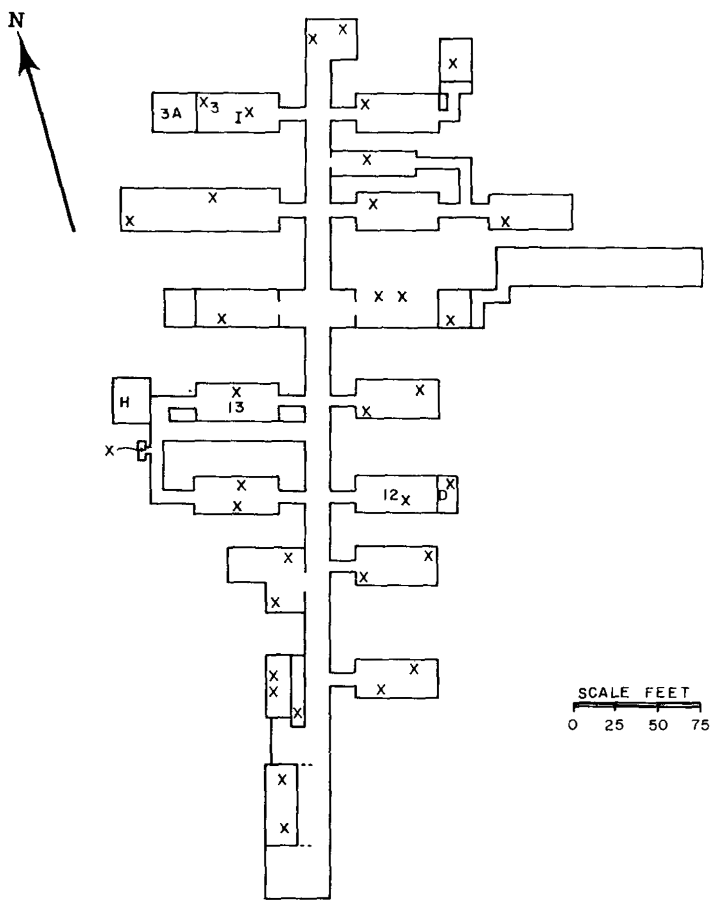

FIGURE 2.—Plan of buildings at Little America V, Antarctica. No. 3 is meteorology building. Intake for air for surface ozone analyzer, indicated by "I", is located about 4½ ft. above building roof. No. 12 is aurora-air glow building. Dobson ozone spectrophotometer, indicated by "D", is on aurora tower at rear of building 12. The roof of the tower is about 25 ft. above the general roof level of the other buildings. Building marked "H" behind No. 13 is the hydrogen shelter where rawinsonde balloons are inflated and released. Smoke sources are indicated by the letter "X".

A detailed description of the instrument and observational procedures has been given by Dobson [3]. At Little America the wavelength pairs designated "A", "B", "C", and "D" [3] were employed whenever feasible. These wavelengths are:

Wavelength pair:	A	B	C	D
Short (Å.)	3055	3088	3114.5	3176
Long (Å.)	3254	3291	3324	3398

During the spring and autumn months the "A" and "B" wavelengths frequently could not be used due to the weak light intensity caused by the low elevation of the sun. During the polar night measurements were made using the moon as a light source; because of the low sensitivity of the instrument only "D" wavelengths could be employed then.

Ozone values were based upon the standard "AD" reduction when the "A" wavelengths were obtainable; otherwise, the values were obtained from "CD" measurements. Zenith cloud values were not utilized in obtaining averaged monthly ozone amounts since a comparison of zenith cloud and direct sun values showed that they were not compatible. All the ozone values must be considered provisional until the instrument is recalibrated upon its return to the United States.

Surface ozone—Figure 2 also shows the physical location of the air intake for the surface ozone analyzer, and nearby sources of atmospheric pollution in the camp.

The air intake was located about 4½ feet above the roof of the Meteorology Office, and at a lesser but variable distance above the snow which covered the roof except for the brief summer season. Each of the permanent buildings contains two diesel oil heaters, with stovepipes discharging the combustion by-products at about 6 feet above the building roofs. As can be seen from the diagram the main part of the camp, and hence the maximum amount of air pollution from this source, is located in the quadrant between east-southeast and south-southwest relative to the air intake.

The glass tube of the intake itself curves around at the top to end in an inverted glass beaker about 3 inches in diameter, which is packed with glass wool to prevent entrance of particulate matter into the ozone measuring device. It was noted that only a few hours' exposure of fresh glass wool in the beaker was sufficient to collect enough soot to be visible, and after about one day the intake surface of the glass wool became completely blackened. The glass wool was changed only when the air flow through the measuring device dropped, not more often than once a month at best. Since replacing the soot-encrusted wool with clean wool did not result in any noticeable change in the instrument readings, it does not appear likely that there was a significant local effect on surface ozone concentration.

3. DISCUSSION OF TOTAL OZONE OBSERVATIONS

As direct sun observations using the "A" and "D" pairs of wavelengths give the most reliable values of total ozone, these values were used on days when such observations were possible. On other days when sun observations using the "CD" pairs of wavelengths were obtained, these ozone values were used, after applying a correction to make them more nearly compatible with the "AD" observations (see next paragraph). Finally, with only the full moon or with very low sun, when neither of the above types of observations was possible, the focused image values on the "D" wavelengths only were used. In all of the computed values, the ozone absorption coefficients as determined by Vigroux [12] and listed by Dobson [3] were the ones applied.

There were several occasions when readings on both the "AD" and "CD" pairs of wavelengths were obtained at nearly the same time, so that a comparison of the two types of readings was possible. Fifty-four such occasions were analyzed, and it was found that on the average the "CD" readings gave 0.055 cm. lower values of ozone than the "AD"

TABLE 1.—*Mean total ozone observations at Little America V, Antarctica, in cm. of pure ozone, reduced to standard temperature and pressure. Number of days' observations in parentheses.*

Month	1957	1958	Combined	Remarks
January	none	0.314 (13)	0.314 (13)	Direct sun AD
February	0.299 (2)	.314 (5)	.310 (7)	Direct sun AD
March	.333 (15)	.335 (1)	.334 (16)	Mostly FIS CD or D
April	.266 (4)	none	.266 (4)	FI moon on D
May	.395 (2)	.349 (1)	.380 (3)	FI moon on D
June	.480 (2)	none	.480 (2)	FI moon on D
July	.346 (3)	.433 (1)	.368 (4)	FI moon on D
August	.536 (2)	none	.536 (2)	FI moon on D
September	.334 (17)	none	.334 (17)	Mostly FIS CD or D
October	.384 (15)	.353 (8)	.373 (23)	Mostly direct sun AD or CD
November	.421 (21)	.399 (1)	.420 (22)	Direct sun AD
December	.316 (3)	none	.316 (3)	Direct sun AD
Mean for all observations 0.360 (116)				

FIS=focused image observation on the sun.
FI moon=focused image observation on the moon.

readings, with a standard deviation in the differences of 0.009 cm. A graph of the 54 differences plotted against air mass and against the "AD" values showed no apparent relationship of the differences to either parameter. All of the "CD" values used in this report were corrected by adding 0.055 to the computed ozone value. (Qualitatively the values from the "D" wavelengths alone also seem lower than the "AD" values for the same time, but in view of the much greater variability of the differences no correction factor was applied to these readings.)

Table 1 shows the mean ozone values obtained by the above methods of observation for each month for 1957 and 1958 and the combined data. Figures in parentheses following each mean value give the number of days' observations on which the mean was based. Figure 3 is a graph of the combined values, with the number of days entered in the plotted circle.

The dark-season observations are too few in number and too variable in value to permit any firm conclusions as to winter atmospheric ozone content over Little America, although their mean indicates winter values higher than the overall annual mean. The more numerous observations in the spring and summer show the total ozone content increasing in the spring to a November maximum, and then decreasing to an average value of about 0.32 in the summer, with little month-to-month change during the summer season.

4. DISCUSSION OF SURFACE OZONE MEASUREMENTS

The mean hourly readings of surface ozone concentrations were extracted from the recorder charts. Gaps in the data exist during periods of malfunctioning or nonfunctioning of the device. Days on which data were missing were completed by linear interpolation of values for the missing hours, when this period did not exceed 6 hours and the change over the missing period was not

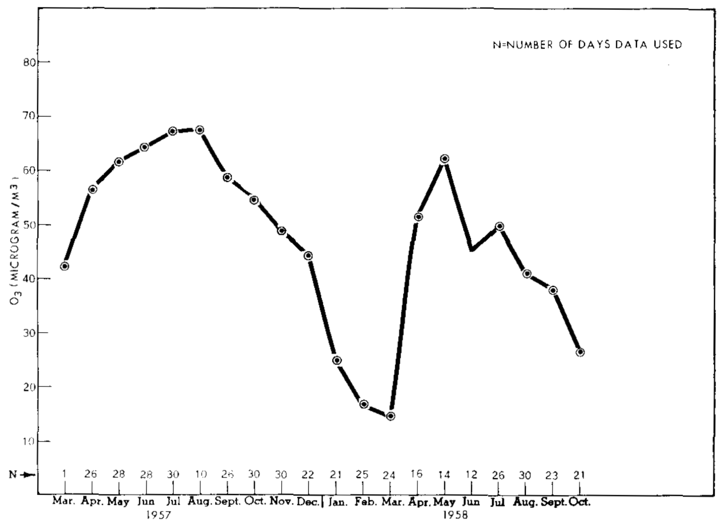

FIGURE 4.—Little America Station monthly average surface ozone concentrations, March 1957 through October 1958.

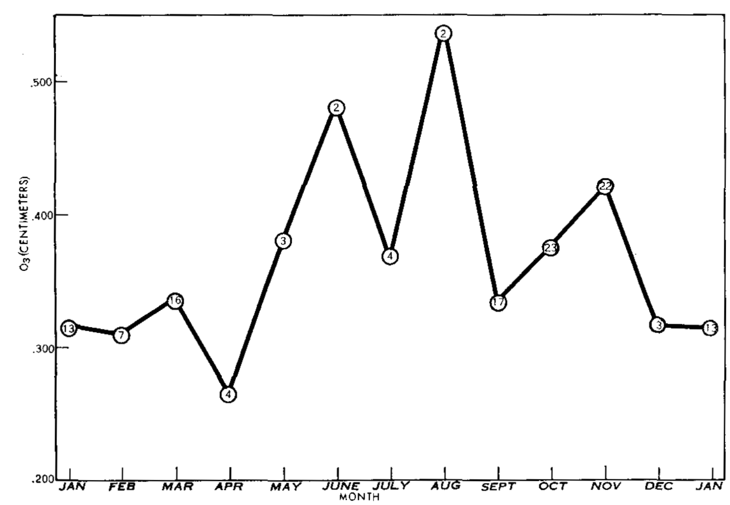

FIGURE 3.—Little America Station total ozone, average of 1957 and 1958. Within circle is number of days' observations.

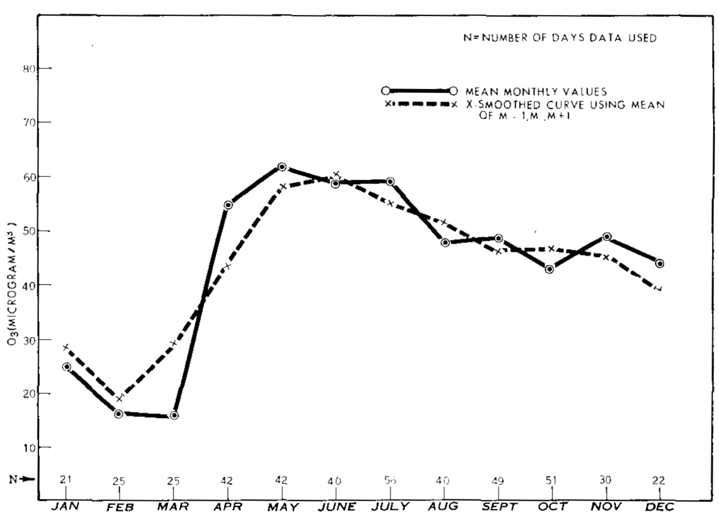

FIGURE 5.—Little America Station monthly average surface ozone concentrations—combined 1957–58 data.

TABLE 2.—*Daily values of surface ozone concentration at Little America V, Antarctica in micrograms m.*$^{-3}$ *Interpolated values are enclosed in parentheses. Means are of observed values only.*

Day (GMT)	1957										1958									
	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
1		52.0	61.9	66.2	65.8	65.5	(65.6)	(45.6)	52.7	40.7	21.5	16.5	21.1	(44.7)	(75.0)	(38.5)	(50.6)	49.3	(50.6)	29.9
2		(51.0)	59.3	63.3	66.9	69.8	(65.3)	48.8	52.7	41.4	22.1	12.0	21.9	(46.3)	81.1	35.1	(58.1)	40.6	53.1	30.4
3		(50.1)	57.3	68.5	62.2	72.2	(64.9)	45.3	51.9	39.1	27.8	13.8	17.6	(47.8)	(77.8)	(36.7)	65.7	26.5	(49.5)	(30.4)
4		49.1	66.1	71.1	64.7	66.3	(64.5)	42.3	53.5	42.0	29.3	20.9	23.0	(49.4)	(74.5)	(38.3)	50.4	36.1	45.8	30.4
5		52.1	65.1	67.8	61.9	53.6	64.2	51.7	52.1	41.6	24.4	16.2	21.0	(51.0)	(71.3)	(39.9)	53.0	39.4	42.1	23.9
6		53.5	60.2	(70.6)	75.9	(58.2)	63.7	61.8	57.5	41.9	19.2	18.5	17.5	(52.5)	(68.1)	(41.6)	(49.3)	33.8	37.5	(25.6)
7		53.5	60.0	73.5	71.8	62.8	64.1	62.0	57.8	35.3	14.1	22.7	12.0	(54.1)	(64.8)	(43.2)	45.7	41.9	38.0	(27.3)
8		53.6	62.8	74.4	69.5	66.9	64.2	59.1	60.3	(37.5)	19.1	21.9	8.3	(55.7)	(61.5)	(44.8)	41.7	44.1	36.3	29.0
9		56.1	52.4	72.4	68.7	69.4	66.9	61.6	53.7	(39.8)	(17.8)	16.8	9.4	(57.3)	(58.3)	(46.5)	41.0	47.3	(36.5)	23.0
10		52.1	61.4	72.3	68.2	72.9	66.4	59.0	53.0	42.0	16.4	19.2	4.8	58.9	(55.0)	(48.1)	50.6	42.4	(36.8)	(22.5)
11		60.1	55.4	72.5	69.9	73.2	69.6	57.0	49.7	46.3	26.2	13.3	7.9	65.2	51.7	(49.7)	57.1	33.8	37.0	(22.1)
12		58.3	62.3	64.9	68.2	(72.8)	73.6	65.3	49.2	47.8	31.2	14.4	7.6	68.3	53.0	51.3	58.0	32.9	(39.0)	(21.6)
13		59.7	59.0	56.6	70.0	(72.5)	66.0	58.3	49.5	49.6	(31.4)	18.2	4.3	65.1	(57.5)	40.5	49.0	41.0	40.9	(21.2)
14		62.0	57.8	61.4	(67.6)	(72.1)	58.8	60.9	52.0	48.2	(31.7)	20.8	6.7	60.0	58.0	43.9	44.5	41.7	(44.8)	(20.7)
15		61.9	55.5	57.1	65.3	(71.7)	56.2	56.7	53.0	37.4	(31.9)	15.7	2.8	57.7	59.6	(53.4)	53.0	44.1	(48.8)	20.2
16		56.4	58.1	59.2	65.6	(71.4)	58.8	53.3	55.8	37.8	(32.1)	12.0	(3.6)	51.7	61.4	62.9	59.2	43.7	52.7	24.2
17		56.6	57.2	56.7	68.1	(71.0)	50.4	44.7	55.2	(39.3)	(32.4)	8.3	(4.4)	46.2	58.9	37.0	54.3	42.0	44.2	22.8
18		(55.7)	61.6	54.9	64.4	(70.7)	64.4	59.9	46.2	40.7	(32.6)	9.5	(5.3)	40.9	65.4	30.6	51.3	43.4	46.5	22.5
19		(54.7)	58.9	51.2	70.6	(70.3)	62.1	53.8	46.6	36.0	(32.9)	9.7	(6.1)	43.0	67.4	43.1	53.8	43.1	37.7	24.8
20		53.8	61.2	44.5	69.9	(69.9)	65.8	57.9	42.0	42.0	33.1	10.3	6.9	49.2	60.2	(49.5)	47.5	42.9	42.6	22.1
21		51.2	66.5	(57.8)	64.0	(69.6)	59.6	61.4	45.9	40.1	30.9	15.5	10.9	51.9	60.4	55.8	48.6	(40.1)	41.2	28.3
22		52.6	65.3	71.0	60.2	(69.2)	51.1	57.7	37.0	51.8	37.4	17.9	7.5	47.9	63.4	59.5	51.0	37.4	22.3	31.7
23		57.8	66.9	67.6	65.8	(68.9)	43.1	49.7	41.8	(54.5)	29.2	21.3	5.9	38.2	64.3	45.0	42.9	39.8	33.8	37.3
24		58.0	65.7	67.5	63.9	(68.5)	48.0	45.8	43.4	(57.2)	31.2	(20.5)	8.5	41.2	66.5	(43.4)	39.5	34.3	31.7	28.8
25		59.9	64.8	63.3	67.7	(68.1)	45.8	48.4	45.4	59.9	21.1	(19.8)	9.2	38.6	(63.0)	(41.8)	40.7	39.1	31.5	(27.2)
26		60.7	61.6	58.9	62.8	(67.8)	48.5	53.6	40.9	53.3	21.0	(19.0)	(22.5)	(44.7)	(59.5)	(40.3)	45.3	46.8	29.4	(25.5)
27	42.1	55.1	69.9	67.7	66.4	(67.4)	52.9	47.8	41.8	55.6	19.8	18.3	35.7	(50.8)	(56.0)	(38.7)	41.4	38.9	32.9	23.9
28	(44.1)	60.8	68.4	67.4	68.4	(67.1)	58.1	51.3	41.3	(48.8)	22.6	21.8	39.8	(56.8)	(52.5)	(37.1)	48.0	47.4	28.1	24.8
29	(46.1)	59.1	(67.8)	64.7	66.9	(66.7)	50.6	51.4	33.9	(42.0)	(21.5)		40.0	(62.9)	(49.0)	35.5	(52.5)	43.8	33.1	28.8
30	(48.0)	63.9	(67.3)	66.4	68.1	(66.3)	42.3	54.6	40.4	(35.2)	(20.4)		(41.6)	(69.0)	(45.5)	(43.0)	(56.9)	44.1	32.9	26.2
31	(50.0)		(66.7)		67.8	(66.0)		58.7		(28.4)	19.3		(43.1)		(42.0)		61.4	48.1		24.2
Mean	42.1	56.5	61.6	64.4	67.0	67.3	58.3	54.7	48.6	44.1	24.6	16.2	14.6	51.5	62.1	45.0	49.8	41.0	37.9	26.5

TABLE 3.—*Hourly mean values of surface ozone at Little America V, Antarctica, in micrograms m.*$^{-3}$ *N is the number of complete days' data for each month.*

Hour ending (GMT)	1957										1958										443-day mean
	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	
01	42.6	54.6	61.1	62.9	65.0	66.3	51.3	53.2	48.0	42.9	24.5	15.7	15.1	52.6	62.1	45.9	49.9	41.1	37.4	25.4	45.9
02	40.5	54.4	61.1	62.2	64.6	65.9	51.4	52.8	47.4	43.1	24.6	15.7	15.1	52.3	62.1	46.3	50.0	40.8	37.4	25.8	45.7
03	38.4	54.6	60.9	61.9	64.2	65.0	52.0	52.8	47.4	42.8	24.5	15.2	14.4	51.6	61.5	47.1	50.3	41.2	37.0	26.5	45.6
04	38.4	55.4	62.1	63.0	64.5	64.6	53.5	53.5	47.3	41.9	24.8	15.2	13.6	51.2	61.0	47.1	50.1	40.9	36.3	26.2	45.8
05	40.5	56.0	61.8	64.1	66.1	66.2	55.0	53.8	47.7	41.7	25.5	15.1	13.7	51.0	60.5	47.5	50.2	41.2	36.7	27.0	46.2
06	40.5	56.7	61.6	64.4	66.5	66.5	56.4	54.3	47.6	42.0	24.9	15.1	13.8	50.8	59.9	46.0	50.2	41.5	37.0	27.6	46.4
07	40.5	57.1	61.6	65.3	66.9	66.7	58.3	53.9	47.8	42.7	25.0	14.9	14.5	50.7	60.5	46.0	50.4	41.0	37.4	27.9	46.7
08	40.5	57.9	60.9	65.1	67.6	66.7	59.9	54.8	47.8	43.1	24.3	15.1	14.0	51.0	60.2	46.2	50.7	40.8	37.4	27.2	46.9
09	42.6	57.4	61.2	65.2	67.4	66.4	60.8	54.5	48.0	42.6	24.6	15.2	14.0	50.6	59.8	45.0	50.3	40.2	38.1	26.1	46.8
10	42.6	57.7	60.6	64.6	67.6	67.6	61.1	54.5	48.3	42.9	24.2	15.4	14.2	51.3	59.6	44.3	50.0	40.5	38.7	26.3	46.8
11	42.6	57.8	61.6	65.5	68.3	68.3	61.5	54.8	48.6	44.1	24.6	15.4	14.5	51.6	60.5	43.7	50.0	40.1	38.3	26.2	47.2
12	42.6	57.9	62.6	66.6	68.7	68.5	62.1	54.9	48.9	45.5	24.8	15.2	14.6	51.3	61.2	44.8	50.4	40.4	39.0	27.1	47.6
13	42.6	57.8	62.2	67.2	68.9	67.8	62.7	56.5	49.1	46.1	24.8	16.2	14.6	51.6	62.3	44.8	50.2	40.9	39.2	26.6	47.9
14	42.6	58.0	62.7	66.6	68.8	69.9	63.7	56.5	49.3	45.6	24.4	17.1	14.6	51.2	63.0	45.8	49.9	41.0	39.7	27.3	48.1
15	44.6	58.1	63.1	66.2	68.8	69.9	63.3	56.6	49.7	45.7	24.6	17.8	15.2	51.4	64.1	46.7	49.6	41.1	39.4	27.5	48.3
16	44.6	58.2	63.3	65.0	68.6	69.9	63.8	56.9	50.0	45.6	24.2	17.8	14.5	51.6	64.8	45.6	49.7	40.9	38.9	27.4	44.2
17	46.9	57.6	61.9	65.1	67.9	68.8	63.2	56.4	50.1	45.4	23.7	18.3	15.0	52.0	64.8	45.6	49.3	41.0	39.1	27.0	48.0
18	46.9	56.9	62.5	65.4	68.2	68.3	62.1	56.1	49.9	44.9	24.1	18.1	15.1	52.4	63.6	44.4	49.6	41.2	39.2	26.8	47.8
19	46.9	55.3	62.1	65.3	68.1	67.9	61.5	55.8	49.6	44.9	24.1	17.5	15.4	52.3	63.8	43.1	49.7	41.5	38.8	27.0	47.6
20	42.6	55.0	61.3	64.0	67.6	66.9	59.9	55.5	49.0	45.1	24.8	16.9	14.7	52.2	63.7	42.9	49.4	41.6	37.9	26.3	47.1
21	40.5	55.6	60.5	62.8	66.2	66.4	57.0	54.2	48.8	44.6	24.6	16.9	14.9	52.0	62.7	41.9	49.2	42.1	37.0	26.0	46.5
22	40.5	55.8	59.7	62.4	65.8	66.9	54.7	53.0	48.6	44.5	24.9	16.9	15.2	51.0	63.2	42.9	49.2	41.3	36.3	25.1	46.1
23	40.5	55.7	60.1	62.6	65.6	66.9	52.3	53.1	48.2	45.3	25.0	16.8	14.7	51.0	63.0	43.6	48.9	40.6	36.0	25.5	45.9
24	40.5	55.3	60.9	62.4	65.8	66.4	50.7	53.5	48.2	45.7	25.2	16.4	14.7	51.0	62.7	43.3	48.4	40.6	36.7	25.1	45.8
Mean	42.1	56.5	61.6	64.4	67.0	67.3	58.3	54.7	48.6	44.1	24.6	16.2	14.6	51.5	62.1	45.0	49.8	41.0	37.9	26.5	46.9
N	1	26	28	28	30	10	26	30	30	22	21	25	24	16	14	12	26	30	23	21	

excessive; otherwise, all incomplete days were omitted. Hourly values for the 443 complete days remaining were then corrected to standard air flow (10.0 liters per minute) and tabulated in units of micrograms per cubic meter (Γ), following the computational procedure given in Regener [9]. The flow rate is measured at the pump exhaust after circulation of the air through the device.

Annual ozone variation—Table 2, in addition to showing the mean daily values of surface ozone for each day of record, also gives the mean monthly value of surface ozone concentration for each month of the IGY during which observations were made. These monthly means are presented in graphical form for each individual month in figure 4, and for the combined 1957–58 data in figure 5. The February-March minimum is followed by a rapid rise in April to maximum concentrations in early winter, with only a gradual decrease through the late winter and spring and a sharp decrease during the summer.

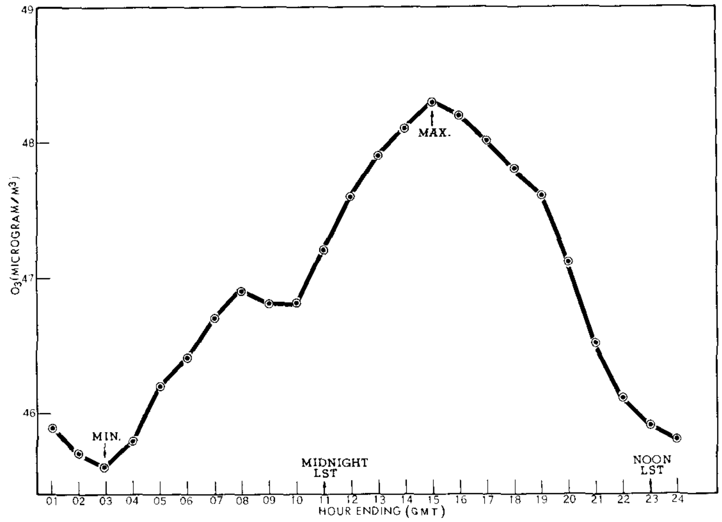

Figure 6.—Little America Station mean hourly surface ozone values, total period of record, 1957–58.

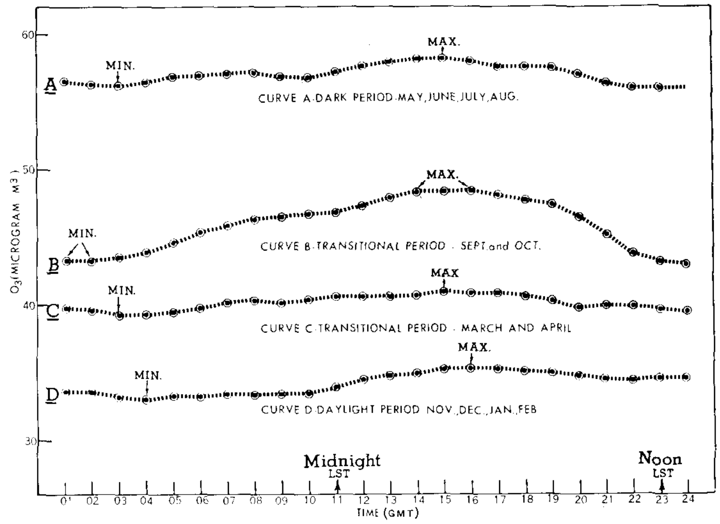

Figure 7.—Little America Station mean hourly surface ozone values by seasons, 1957–58 data.

Diurnal ozone variation—Table 3 shows the mean values of ozone concentration for each month by hour of the day, with values in micrograms per cubic meter and time in Greenwich, 11 hours later than standard time at Little America. Figure 6 gives the mean hourly values for all of the observations, while figure 7 depicts the mean hourly values by season as labeled. The curve in figure 6 shows a maximum at 0400 LST, and a minimum 12 hours later at 1600 LST. Although all of the seasonal curves plotted show the same general pattern, the daily variation is most regular and has the largest amplitude in the spring months of September and October.

The daily variation of surface ozone concentrations at mid-latitude plains stations has been found to vary in a manner which suggests a strong relationship to atmospheric thermal stability. During the day, peak ozone concentrations usually occur during the afternoon, while the minimum concentrations are found during the late evening or early morning hours. It has been suggested that the physical mechanism which causes the variation is due to an imbalance between the rate of ozone destruction at the earth's surface and the resupply processes from the higher tropospheric layers. The increased stability associated with the nighttime formation of a surface radiative inversion reduces the downward transport of ozone to the value where the rate of destruction exceeds the resupply; therefore, during the night, surface concentrations may approach zero. The relatively greater afternoon concentrations are attributed to the greater downward transport associated with instability mixing.

At mountain stations the daily surface ozone variation is usually found to be very small (Bowen and Regener [1]). However, recent results from studies made near the summit of Mauna Loa (Price and Pales [8]) have indicated that daily surface ozone variations may be strongly influenced by local mountain-valley wind circulations.

The terrain and the low-level atmospheric thermal structure found at Little America differ markedly from the mid-latitude environments where the majority of surface ozone measurements have been made. The absence of any vegetation and the extremely low atmospheric turbidity may result in lower ozone destruction rates. The low-level atmospheric thermal structure is dominated by a strong surface inversion which exists almost continuously except during the summer months when it may disappear completely or exist weakly as an isothermal layer. The above factors as well as the total absence or continuous presence of the sun would be expected to cause the amplitude of the diurnal ozone variation to be very small.

In order to investigate the magnitude and phase of the daily ozone oscillations, the data were examined by means of harmonic analysis. The results, which may be

Table 4.—*Harmonic constants for surface ozone diurnal and semidiurnal variations at Little America V, Antarctica*

Month	Year	A_1 micrograms per m.^{3}	$A_1/\bar{O}_3$ percent	t_1 hr. after midnight (165° W.)	A_2 micrograms per m.^{3}	$A_2/\bar{O}_3$ percent	t_2 hr. after midnight (165° W.)
January	1958	0.20	0.8	15.7	0.13	0.5	11.5
February	1958	1.45	9.0	6.2	.33	2.0	4.7
March	1958	.60	4.1	7.1	.15	1.0	.3
April	1957, 1958	.83	1.5	1.6	.05	.1	5.7
May	1957, 1958	.77	1.2	5.4	.97	1.6	4.5
June	1957, 1958	1.21	2.2	22.9	.90	1.6	3.9
July	1957, 1958	1.10	1.9	1.1	.18	.3	6.9
August	1957, 1958	.90	1.7	3.7	.19	.4	4.3
September	1957, 1958	3.75	7.8	1.9	.77	1.6	6.2
October	1957, 1958	1.12	2.8	1.9	.72	1.8	4.8
November	1957	1.19	2.5	4.5	.17	.3	5.1
December	1957	1.72	3.9	5.2	.65	1.5	.3

A_1=amplitude of diurnal oscillation; A_2 amplitude of semidiurnal variation.

$\frac{A_1}{\bar{O}_3}, \frac{A_2}{\bar{O}_3}$=Relative amplitude where $\bar{O}_3$ is mean monthly ozone concentration.

t_1=Time at which diurnal oscillation reaches its maximum value (A_1).

t_2=Time at which semidiurnal oscillation reaches its maximum value (A_2).

subject to errors due to the short period of record, are presented in table 4.

As anticipated the amplitudes are quite small. In general the diurnal variations are greater than the semidiurnal; however, during May the semidiurnal amplitude exceeds the diurnal. Since the thermal stability variation is greater in the summer than in the winter, one might predict that the relative amplitudes should be greater in the former season than in the latter. The data verify this prediction as the relative diurnal amplitudes average 4.6 percent for the summer months (December-January-February) and 1.9 percent for the winter months (June-July-August). The semidiurnal averages, although smaller, show an average relative amplitude 1.6 times greater in the summer than in winter.

The phase of the ozone diurnal oscillation exhibits a rather large variation which may be due to the short period of record. However, the time of the maximum usually occurs during the early morning hours. The early morning maximum tends to indicate that factors other than thermal stability variation may also be very important in determining the phase and amplitude of the diurnal ozone variation in polar regions.

Since the camp was on a 24-hour-a-day work basis, and since most or all of the camp contaminants consisted of smoke from heating stoves in 24-hour operation, there does not appear to be a diurnal cycle of camp contamination which could account for the phase of the observed diurnal variation of ozone concentration.

One possible factor which might influence the diurnal ozone variation is the daily worldwide pressure oscillation. The mass convergence associated with this pressure wave may cause an increase in the ozone density. In order to determine whether such a relationship exists, a harmonic analysis was made on all the available surface-pressure data obtained at the present and previous Little America sites. It is well known that the diurnal pressure variation is influenced by local weather and topography which complicate its worldwide characteristics. The semidiurnal variation, however, is worldwide and is the more

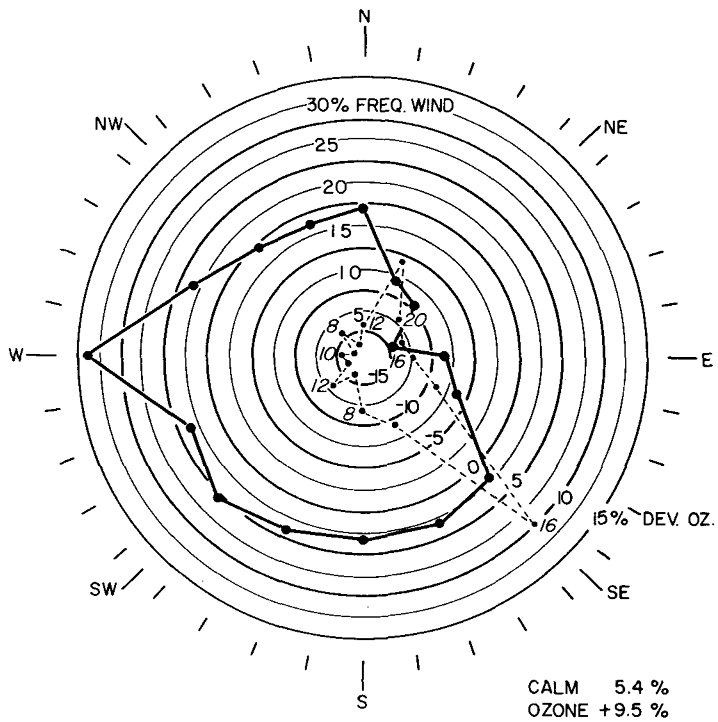

FIGURE 8.—Surface ozone and wind rose, Little America Station, June 1957 (from [4]). Heavy line connects values of percent deviation of surface ozone from monthly average for the various compass points. Dashed line connects percent frequency of occurrence of wind from the various directions. Numerals beside plotted wind points are average wind speed in knots.

important oscillation, especially in the polar regions. This fact is shown quite well by the harmonic constants for pressure in table 5. The semidiurnal wave exhibits greater uniformity in phase angle and amplitude than does the diurnal wave.

A comparison of the harmonic constants for pressure with those for ozone indicates that there is little or no relationship between them. Therefore, from these limited data, it appears that the periodic daily pressure variation has little influence on the diurnal ozone oscillation.

Ozone and wind rose—Wind and ozone roses were constructed for selected months to show both the relative frequency of the different wind directions and the variation in surface ozone concentration with wind direction. This was done by plotting for each compass direction the percentage of time in the month during which the wind blew from that direction, based on the hourly surface wind observations; the mean value of surface ozone hourly readings for those hours when the wind blew from a specified direction was computed, and the result plotted as a percentage deviation from the overall mean monthly ozone value.

The June 1957 Little America rose (fig. 8) shows positive deviation of ozone amounts with westerly and calm winds, and negative deviation with easterly winds. In August 1958, the computations show very broadly the same general pattern although the rose is more irregular and

TABLE 5.—*Harmonic constants for surface pressure diurnal and semidiurnal variations at Little America sites, Antarctica*

Month	Year 19—	A_1 (mb.)	t_1 hr. after midnight (165° W.)	A_2 (mb.)	t_2 hr. after midnight (165° W.)
January	29, 30, 35, 41, 58	0.00	----------	0.10	1.5
February	29, 34, 40, 58	.00	----------	.10	10.2
March	29, 34, 40, 57, 58	.10	10.2	.10	10.7
April	29, 34, 40, 57, 58	.07	1.7	.10	10.5
May	29, 34, 40, 57, 58	.17	15.4	.10	10.4
June	29, 34, 40, 57, 58	.10	13.8	.17	9.5
July	29, 34, 40, 57, 58	.10	16.7	.14	.0
August	29, 34, 40, 57, 58	.14	15.7	.07	10.5
September	29, 34, 40, 57, 58	.27	15.9	.10	11.9
October	29, 34, 40, 57, 58	.00	----------	.14	11.3
November	29, 34, 40, 57	.10	7.9	.17	9.4
December	29, 34, 40, 57	.03	22.2	.03	10.6

A_1=Amplitude of diurnal pressure oscillation.
A_2=Amplitude semidiurnal pressure oscillation.
t_1=Time of occurrence of A_1.
t_2=Time of occurrence of A_2.

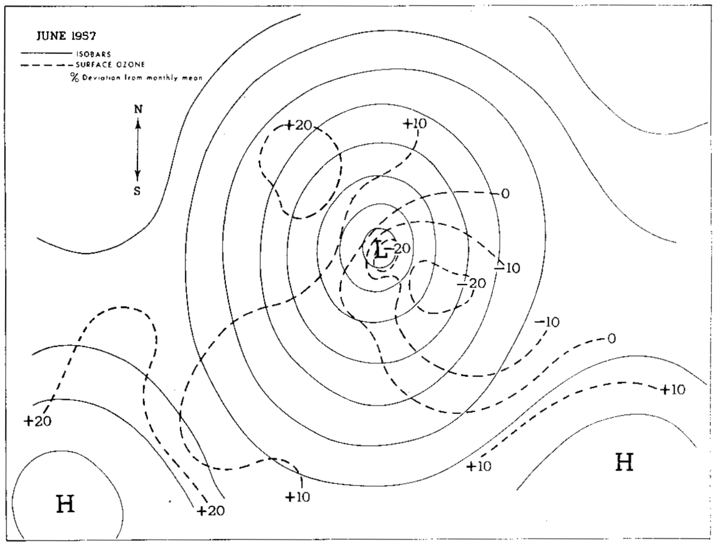

FIGURE 9.—Percent deviation of surface ozone concentration from monthly mean, and sea level pressure pattern, Little America, June 1957. Each value for percent of deviation was plotted on model pressure pattern at position of Little America in the surface pressure pattern at the time of the ozone observation.

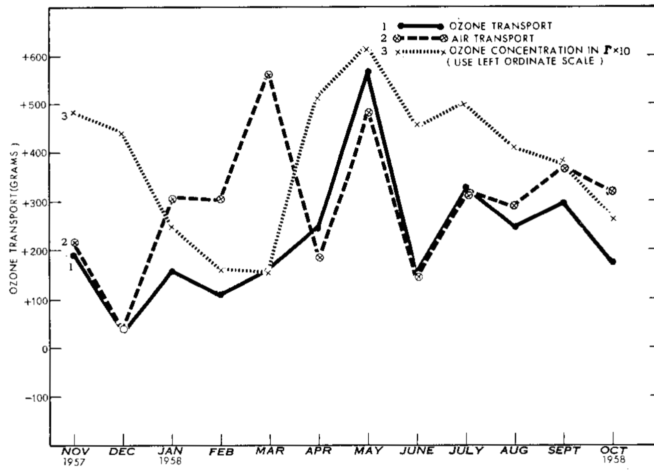

FIGURE 10.—Little America Station mean monthly surface ozone and meridional mass transport of air and ozone.

the calm wind deviation is negative. February 1958 shows positive deviations with all wind directions from WSW through N to NE, while with calm winds and most of the other wind directions there are negative deviations. All of these months show a net transport of both air and ozone from the continent northward to the ocean.

Relation with sea level pressure field—The relationship of surface ozone concentration to the sea level weather chart is illustrated in figure 9. Charts similar to the one for June 1957 shown here were prepared for each month April through September 1957 by plotting the deviation of the ozone concentration at 0000, 0600, 1200, and 1800 GMT from the mean monthly concentration. Each value was plotted in the model pressure pattern by determining the position of Little America with respect to the surface weather pattern at the time of the observation. The 6-hourly synoptic maps prepared at the IGY Antarctic Weather Central were utilized in determining the relationship.

The surface ozone pattern depicted by the June 1957 chart is typical of all the charts. In general, the lower values were found to occur in the southeast quadrant of the surface Low. Cyclones entering the Ross Sea usually approach Little America from the northwest. These negative deviations may be the result of the advection of air with lower ozone concentrations from off the ocean. Positive deviations were located in the northwest quadrant of the Low and in the cold anticyclone occasionally found over the Ross Sea. The advection of ozone-rich air from the continent into the rear of the cyclone may account for the maximum observed there. The positive deviations found in the high pressure regions may be the result of the downward transport of ozone by subsidence processes usually associated with a polar anticyclone.

Ozone transport—Table 6 shows the monthly values of volume transport of air and mass transport of ozone along the meridian at Little America. These values were obtained as follows: the net meridional component of wind for each day was computed from the 24 hourly wind observations and multiplied by the average ozone concentration for that day to give daily ozone mass transport; these were then summed algebraically to give the total monthly and finally annual transport. In this case, when daily values for ozone concentration were missing, linearly interpolated values were used (parenthetical values in table 2). Units for air transport for the month are 10^6 m.^{3} of air through an area of 1 m.^{2} normal to the meridian at anemometer height (about 10 m.). For the monthly ozone transports the units are grams of ozone through an area of 1 m.^{2} at anemometer height, assuming that the ozone concentration is the same at intake height and anemometer height. Each month shows a northward (positive) component of the air transport with a minimum in December and maxima in March and May. The ozone transport northward shows a minimum in December and a maximum in May (the low March ozone value outweighs the high air transport). In figure 10 are presented graphs of the meridional mass transport of ozone, the meridional volume transport of air, and the mean monthly surface ozone values, the latter taken from figure 4.

TABLE 6.—*Meridional air and ozone transports at Little America*

Month	Net meridional air transport (10^6 m.^{3}/m.^{2})	Net ozone transport (gm./m.^{2})
November 1957	+4.399	+194.4
December 1957	+.682	+33.6
January 1958	+6.172	+156.4
February 1958	+6.070	+107.8
March 1958	+11.288	+163.1
April 1958	+3.781	+242.2
May 1958	+9.667	+567.5
June 1958	+2.973	+146.5
July 1958	+6.351	+324.7
August 1958	+5.802	+247.9
September 1958	+7.445	+297.2
October 1958	+6.305	+171.2
12 months	+70.935	+2652.5

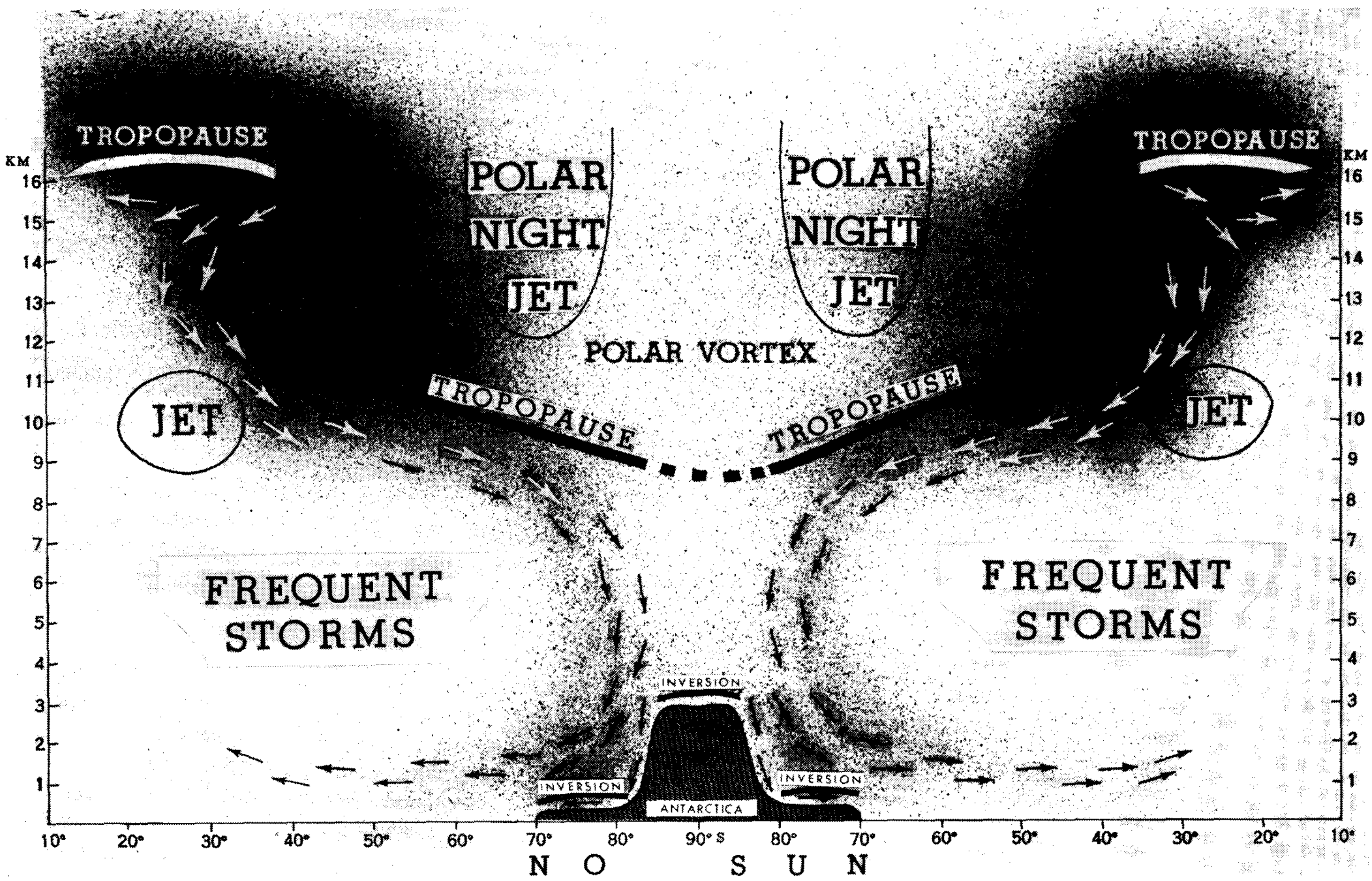

FIGURE 11.—Schematic representation of winter ozone cycle in Antarctica.

5. POLAR-NIGHT OZONE BUDGET AND CIRCULATION

Referring to figure 4 we see that during 4 months of the dark period, June through September 1958, the surface ozone content was fairly constant at 38 to 50 micrograms m.$^{-3}$. During this same 4-month period the net ozone flow northward from Little America was 1016 gm. m.$^{-2}$ (see table 6 and fig. 10). If there is to be a steady state then as much ozone must flow in as flows out, since we assume no ozone is created or destroyed by photochemical or other means.

The ozone influx can occur in the stratosphere or in the troposphere. Since ozone is usually found in greatest amount in the lower stratosphere one would expect that this layer would be the most likely source of supply of ozone to the surface air over Antarctica. However, there are two difficulties facing this explanation. First, the strong winter circumpolar jet stream in the low stratosphere (Moreland [7]) would discourage significant transport of ozone into the interior of the Antarctic continent (Wexler [13]). Second, even if there were a significant stratospheric influx of ozone into the interior, it would require many days of radiative cooling over the continent for this air to sink through the stable stratosphere, then through the tropopause into the troposphere, and to descend into and flow out with the surface layer of air.

For example, on August 6, 1957, a day of coldest stratosphere at the South Pole (−91° C. at 50 mb.), the potential temperature at 100 mb. was 360° A.; at the top of the surface inversion (555 mb.) it was 286° A., and at the surface (702 mb.) it was 255° A. Even a large cooling rate of 5° C. day $^{-1}$ would require the same air to remain over Antarctica for more than 20 days in order to reach the surface, an unlikely event. Of course, turbulent transport downward would occur, but in view of the strong stability of the stratosphere and surface layer, this would be a slow process too.

It thus appears that the major influx of ozone into Antarctica occurs in the troposphere above the surface layer. The winds responsible for this transport are associated with the vigorous winter storms which move around and into the continent, transporting such vast quantities of real and latent heat that tropospheric temperatures show very little decline during the dark period, April to September (Wexler [13]). In addition to real heat and water vapor these same large eddies can also transport into Antarctica ozone from lower latitudes. This ozone, which is manufactured photochemically in the sunlit stratosphere, probably enters the troposphere through the tropopause gap associated with the mid-latitude (30°–35° lat.) jet stream. (See fig. 11.) It is then caught in the undulating westerly current, and makes

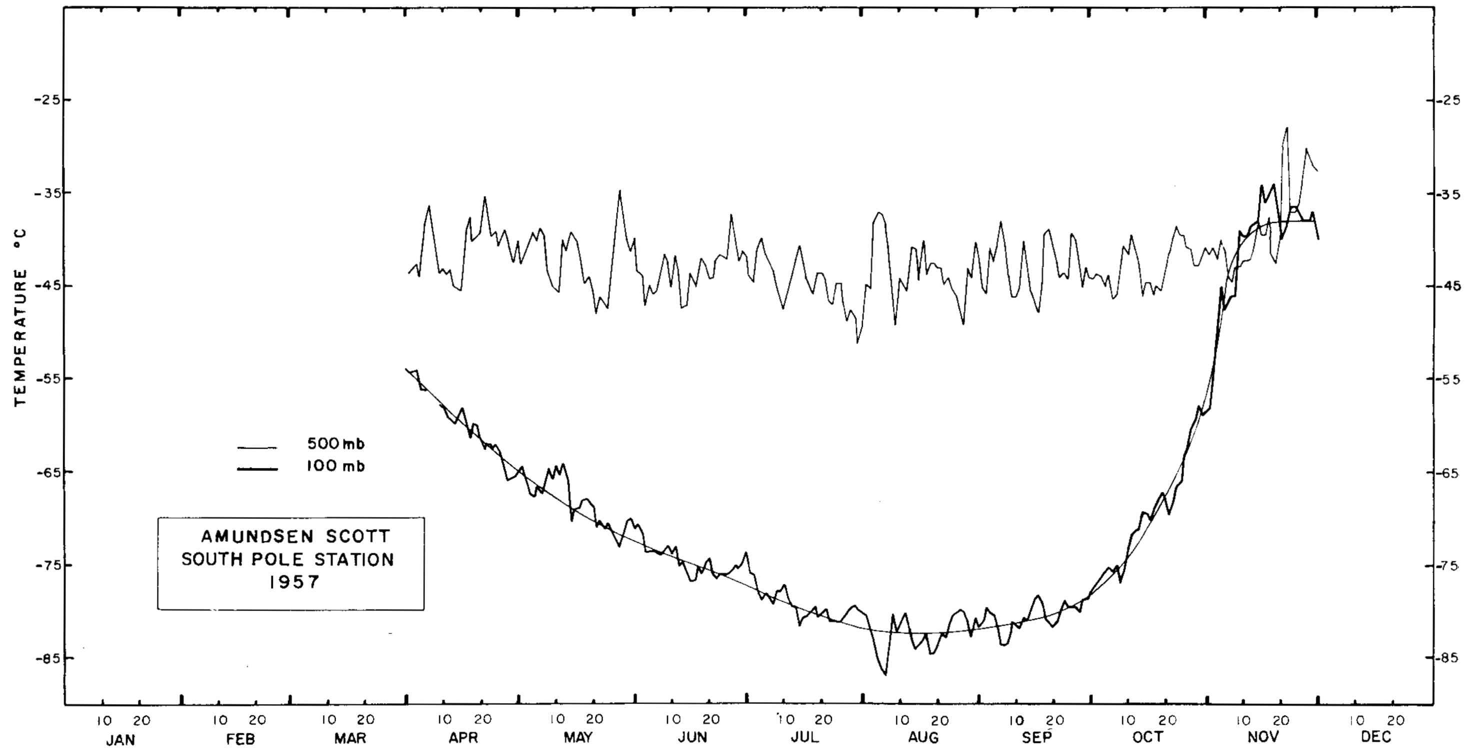

FIGURE 12.—Daily temperatures and seasonal trend, 500 mb. and 100 mb., South Pole, 1957.

its way southward to Antarctica where the air sinks, becomes part of the 2–3-km. thick surface layer, and flows northward. Very little ozone is shown crossing the polar-night jet into the center of the stratospheric polar vortex.

If the principal influx of ozone into Antarctica occurs in the middle and upper troposphere, what concentration of ozone is required? We can compute this roughly in two ways: assume a fictitious Antarctic continent bounded by the 72° S. latitude circle (area 12.5×10^6 km.^{2} compared to the actual 13.5×10^6 km.^{2}). Because of lack of information elsewhere on the Antarctic coast we shall assume first that the Little America mean monthly ozone transport applies to the entire coast. At Little America the 1000–700-mb. layer (which extends from sea level to 2.5 km.) is the layer of outflow in June, July, and August (Court [2], p. 69). If we assume that the surface ozone transport is constant through this layer, this first model results in a northward flow of 31.8×10^{12} gm. of ozone during June–September 1958.

Since, however, the ozone flow across the coast depends on the mass movement of air across the coast, a second computation was made based on values for the entire coast worked out by Rubin [10] for June and December 1958, while in residence at the Soviet IGY Station, Mirny. Later, on his return to Washington where the original U.S.-Antarctic radiosonde observations were available, Rubin corrected these values slightly and completed the computations for the period June through December 1958. These were calculated for tropospheric layers 850–700 mb., 700–500 mb., and 500–300 mb. The mass transports through the surface layer, 850–1000 mb. (near sea level) were obtained by extrapolating downward Rubin's monthly values. In this computation the ozone mixing ratio observed at Little America was assumed for the entire Antarctic coast, taken as the 72° S. latitude circle.

Based on these assumptions and the Little America observations we find that during the 4-month period, June–September 1958, when the surface ozone concentration at Little America was fairly constant at 38 to 50 micrograms m.$^{-3}$, the total ozone *outflow* across the Antarctic coast was 72.8×10^{12} gm., or a little more than twice the transport computed by the first simple model. We shall use the larger transport figure to see if the required ozone concentration in the inflow layer 700 to 300 mb. is a reasonable value. During this same period the air *inflow* in the layer 700 to 300 mb. (2.5 km. to 8 km., the tropopause) was 26.7×10^{20} gm. Thus the ozone concentration in this upper tropospheric layer required to maintain a steady state was 2.72×10^{-8} gm. ozone (gm. air)$^{-1}$ or 1.64 parts per hundred million (pphm) by volume. This concentration compares quite well with the average value in the 700–300-mb. layer observed by ozonesondes at Halley Bay, Antarctica (75°31′ S., 26°36′ W.) on January 24 and July 3, 1958 (MacDowall [6]).

Thus, it appears that tropospheric advection of ozone can by itself account for the high values of surface ozone

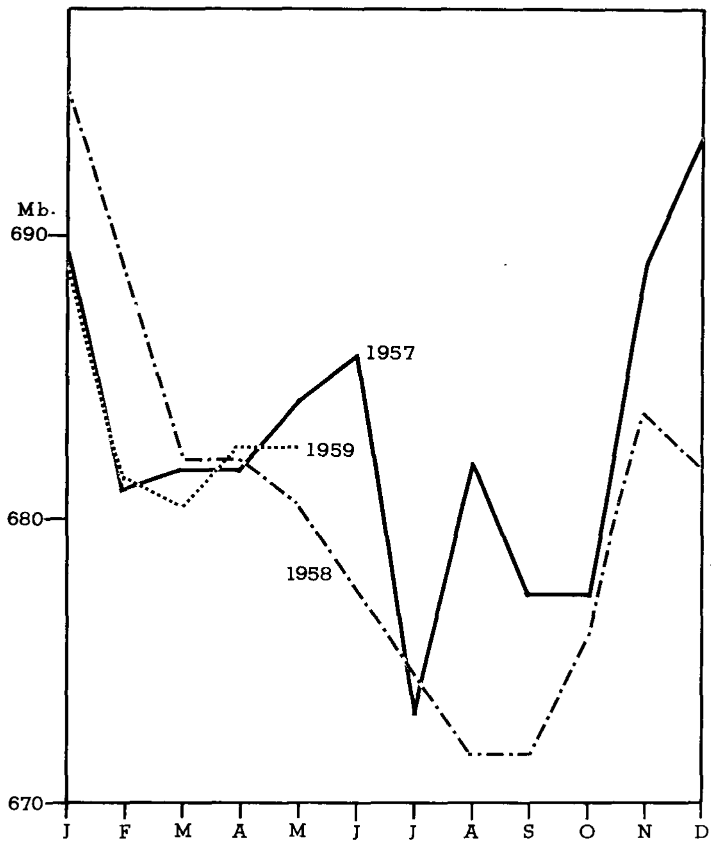

FIGURE 13.—Average monthly surface pressure, South Pole.

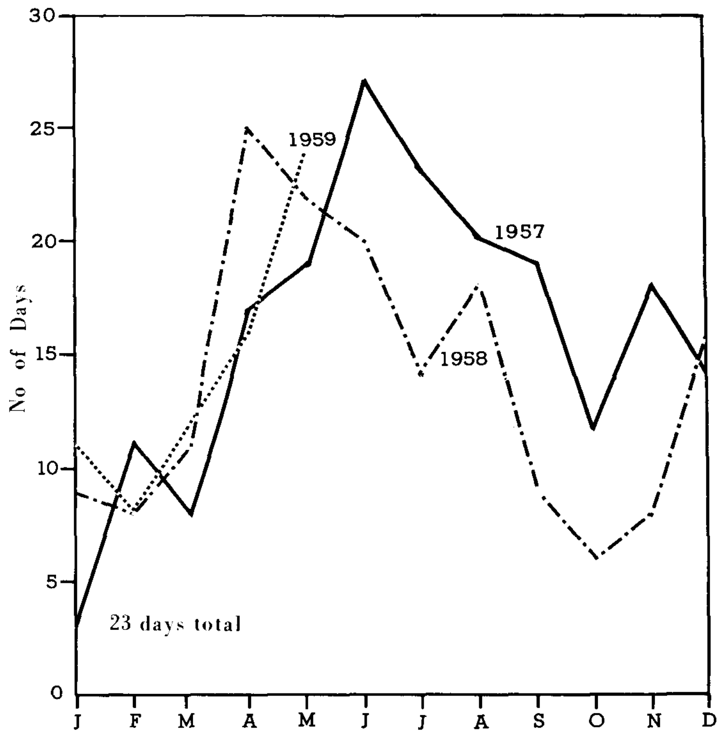

FIGURE 14.—Number of clear days, by months, South Pole. Observations were made on only 23 days in January 1957.

without calling on contributions from the stratosphere over Antarctica. Even the large increase from 15 micrograms m.$^{-3}$ in March to 62 in May 1958 can be accounted for by the inward advection of tropospheric air containing observed concentrations of ozone.

The figures in table 6 require an average of 250×10^{12} gm. sec.$^{-1}$ of air leaving Antarctica in the 0–2.5-km. layer from June–September, and 252×10^{12} gm. sec.$^{-1}$ of air entering Antarctica, or seemingly a near balance. However, even an imbalance of 2×10^{12} gm. sec.$^{-1}$ would still result in an increase in average surface pressure by over 100 mb. in 4 months; the transport figures are not accurate enough to determine precisely the small difference between the two large numbers—inflow and outflow. Nevertheless, changes in monthly mean pressures at interior stations in Antarctica generally agreed in sign with the preliminary estimates of mass advection across the Antarctic coast for May–July and November–December 1958, despite the fact that possible stratospheric influences were neglected (Rubin [10]).

To complete the air mass cycle, descent of air over Antarctica is required with an average downward velocity of about 2 km. day^{-1}. For the temperature lapse rates observed in the mid-troposphere over Antarctica this means a cooling of about 5° C. day^{-1} *if* the tropospheric temperatures are to remain essentially constant from day to day. This cooling must be done by radiative losses and is too high by a factor of 2 compared to cooling rates observed at the South Pole station and at the Hallett Station (72°18′ S., 170°18′ E.) during April-June 1959. The balloon-borne radiometer developed by Suomi et al. [11] was used for this measurement and fuller results will be published later. If the cooling rate is not large enough to permit sinking of air at the required steady-state rate then local heating must result. The large day-to-day fluctuations of temperature at 500 mb. during the 1957 winter at the South Pole (fig. 12) (Moreland [7]) show that the temperatures are not "essentially constant," but whether these fluctuations are caused primarily by variations in advection or by variations in sinking and cooling rates is still to be determined.

During the remaining 3 months for which the preliminary advective rates are available, i.e., October, November, and December, there was an outward flow of 308×10^{12} gm. sec.$^{-1}$ in the 1000–700-mb. layer and an average inward flow of 350×10^{12} gm. sec.$^{-1}$ in the 700–300-mb. layer, seemingly a larger imbalance than in the June–September period. The presence of solar radiation in October–December should decrease the free air radiative cooling rates and thus decrease the compensating downward velocities. This should cause air to accumulate in the troposphere and thus should increase the surface pressure. As may be seen in figure 13, the South Pole station pressures are larger in summer than in winter by about 10 mb., in agreement with the above reasoning.

The fact that sinking of air in the troposphere is more intense in the polar night than in the day is also indicated by the marked increase in the number of clear days during the polar night at the South Pole (fig. 14). This increase is also found at Byrd Station (80° S., 120° W.), and is present at Little America but less distinct because of the coastal location and influence of storms. Since cloudless days with the sky obscured by wind-blown snow are counted as cloudy days and since this condition is more frequent in the windier winter, the contrast may be more marked than shown in figure 14. The more vigorous sinking motions in winter would tend to dissolve cloud systems both by local warming (if the radiative cooling rate is not sufficiently large) and by bringing down drier air.

In closing this section on the ozone budget it is of interest to examine briefly the water vapor budget. Loewe [5] has estimated that the transport of water vapor across 71° S. is 1.35×10^{18} gm. yr.$^{-1}$ corresponding to an average of liquid precipitation over Antarctica of 10 cm. yr.$^{-1}$. This means an average of 0.45×10^{11} gm. sec.$^{-1}$ inflow of water vapor which is deposited as precipitation in Antarctica during the 4 months of the dark season, June–September, when the average inflow of air is 2.5×10^{14} gm. sec.$^{-1}$. Thus, the mixing ratio of the precipitated water vapor is 0.18×10^{-3} gm. gm.$^{-1}$ or 0.18 gm. kg.$^{-1}$.

This value can be compared with the precipitable water content of the air column from 700 to 300 mb. over Hallett Station taken as typical of air entering Antarctica, minus that over the South Pole taken as typical of the air after precipitation has occurred. For the period, June–September 1958, this difference, expressed in gm. kg.$^{-1}$ of the air mass above 700 mb., is 0.10 gm. kg.$^{-1}$ which is smaller than the presumed winter precipitated amount, 0.18 gm. kg.$^{-1}$. It is probable that this latter figure is too large since the winter precipitation is small compared to the other seasons.

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